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# UV/VIS Response Based Fuzzy Logic for Health Assessment of Transformer Oil

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## Abstract

UV-Spectrophotometer response is a nonintrusive test used to determine the transformer integrity. Information about the health of the power transformer that can be use to plan cost, maintenance, relocation and operational criteria can be accurately interpreted using UV-Spectrophotometer. As UV scan can only show the pictorial information of the age of the oil hence it is not advantageous in all aspects. In the presented paper a Fuzzy logic method to determine the health assessment of the transformer oil introduced. The Fuzzy logic uses the UV/VIS spectroscopy absorbance values of the transformer oil which are in service at several locations. The Fuzzy logic method is designed so that the results of transformer oil can be examined quickly and automatically. The results obtained are interesting and accurate.

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Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).*Keywords:* Aging; fuzzy logic; transformer oil; Ultraviolet spectrophotometer.

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## 1. Introduction

Transformer is the key element in the transmission and distribution system for maintaining the power system reliability. Transformers are used for varying the voltage and current levels by maintaining same power transfer (not required). However, if (not required) a fault near a transformer affects the transformer electrical circuit, bushing, core and clamping structure, tap changers, cooling medium, tank, transformer oil and many. Vice versa the faulty behavior of these components affects the transformer operation. Consequently, an occurrence of fault in the transformer disturbs the power system operation within a range leading to non-uniform power supply. The fault occurrence cannot be avoided at all times but complete monitoring of the transformer condition [1] is useful in taking precautions. The monitoring can be done on any part of a transformer and oil which forms coolant part of transformer behaves exactly with the abnormal operation transformer. The aging of the oil is also an important aspect which maintains the steady operation of transformer. Various tests [1, 7] on transformer oil can be done to ensure exact operation. Nowadays new monitoring and diagnostic technologies [1, 4, 6, 8, 11-13] are introduced for the purpose of condition assessment of transformers. The various tests which can be done on transformers oil are viz Dissolved gas. Analysis (DGA), Sweep frequency response analysis (SFRA), Tan Delta tests, Breakdown voltage

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(BDV), Interfacial tension (IFT), and Ultraviolet spectrophotometer (UV/VIS). The DGA test is done so that the level of the gases present in the oil can be determined. It is a very efficient way in monitoring the oil health and the process is a bit lengthy. SFRA is an OFF line testing method and it can be carried out for any voltage rating of Power Transformer, Generator Transformer and Distribution Transformer. The measurement of SFRA can be a part of regular transformer maintenance. The SFR Analyzer identifies the core movement, winding deformation and displacement, faulty core ground, partial winding collapse, hoop buckling, broken or loosened clamping structures, shorted turns and open winding abnormalities in the transformer before they lead to failure. The Technique of SFRA is a major advance in transformer condition monitoring analysis.

Break down voltage (BDV) method measures the stability of the oil to with stand electric stress. The measurement of break down voltage, indicate the presence of the contaminants such as water or conducting particles. Tan-Delta test Tan Delta, also called Loss Angle or Dissipation Factor testing, is a diagnostic method of dielectrics present in a transformer to determine the quality of the insulation. This is done to predict the remaining life expectancy and in order to prioritize cable replacement and/or injection. It is also useful for determining what other tests may be worthwhile. Interfacial Tension (IFT) The interfacial tension between oil and water provides a means of detecting soluble polar contaminants and products of deterioration.

Besides these methods UV Spectrophotometry is a method which provides a platform for visual identification of the age of the oil. Though the method is not supreme compared to the other methods but it got some advantages in terms of accuracy and visualization. UV/VI Spectrophotometer is a technique used for the ageing analysis of the transformer oil with respect to the contamination present in it. The oil gets contaminated mainly due to ageing, acid, sludge, moisture and dust particles due to which the oils chemical and physical properties changes. The Ultraviolet spectrophotometer is an OFF line test, this test method characterize by spectrophotometer the relative level of dissolve decay products in mineral insulating oil of petroleum origin.

Visual identification will be efficient only if a person conversant with the technical aspects. Hence the present paper concentrates on using expert system based on UV/VI Spectrophotometer response for determining the health assessment of the transformer oil. A decision tree is used to automatically identify the age of the oil. As the test method is applicable to compare the extent of dissolve decay products for oil in service, seven samples of transformer oil from different substations are collected and analyzed using UV/VI Spectrophotometer. These oil samples are scanned using UV scan and the absorbance and wavelength values obtained are used to feed the fuzzy logic for identification of the dissolved decay product.

## 2. UV Spectrophotometer

UV Spectrophotometer is an accurate method to analyze the impurities and determining age based on it. The ultraviolet spectroscopy refers to absorption spectroscopy in ultraviolet visible spectral region. This test is generally carried out on transformer oil by using light absorbing properties of the sample. The absorption in visible range directly affects the perceived colour of the chemical involved. This test method is applicable to compare the extent of dissolve decay products for oil in service. A spectrophotometer measures the transmission, absorption or reflection of the light spectrum for the given wavelength.

The Beer’s law provides a linear relationship between absorbance and concentration of an absorber of electromagnetic radiation such as:

$$A = a_{\lambda} \times b \times c \tag{1}$$

Where  $A$  is the measured absorbance,  $\lambda$  is a wavelength dependent on absorption coefficient,  $b$  is the path length, and  $c$  is the sample concentration, also:

$$A = \epsilon_{\lambda} \times b \times c \tag{2}$$

where  $\lambda$  is the wavelength dependent on the molar absorption. The  $\lambda$  subscript is often dropped with the understanding that a value for  $\epsilon$  is for a specific wavelength. If multiple species that absorb light at a given wavelength are present in a sample, the total absorbance at that wavelength is the sum due to all substances:

$$A = (\epsilon_1 \times b \times c_1) + (\epsilon_2 \times b \times c_2) + \dots \tag{3}$$

The subscripts 1, 2 refer to the molar absorption and concentration of different absorbing impurities present in the sample. Experimental measurements are made in terms of transmittance  $T$  which is defined as:

$$T = P / P_o \tag{4}$$

where  $P$  is the power of light after it passes through the sample and  $P_o$  is the initial power of the light. The relation between  $A$  and  $T$  are defined as:

$$A = -\log(T) = -\log(P/P_o) \tag{5}$$

UV/VIS has been in general use for last 35 years and over this period has become most important analytic instrument. The UV spectrophotometer provides reasonable information on the power transformer to plan relocation and operational criteria.

### 3. Experimental Setup and Procedure

An experiment is carried out to obtain the absorbance values of various samples of transformer oil. The experiment has been done according to ASTM D-6802. Initially the UV Spectrophotometer is zeroed with spectral grade heptanes. During this process heptane is placed in 10mm path length glass cuvette, which is installed in UV/VI spectrophotometer. The cuvette with Heptane is then placed in the reference position in the instrument. The second cuvette is filled with the transformer mineral oil sample to be tested. The cuvette holder and cuvette containing the Heptane and transformer oil is pictorially represented in Fig.1.



Fig. 1. Cuvette holder and cuvette containing oil sample

The cuvette with oil is placed so that the absorbance curve of the mineral oil can be determined. The absorbance curve is obtained from the instrument which scans in the range of 360-600nm. The graph is obtained between wavelength versus absorbance of the given oil samples. The relationship exists between the absorbance curve and the total amount of dissolved decay products in mineral insulating oil. The absorbance curve to the shorter wavelength indicates that the oil is new. The shift of the absorbance curve to shorter wavelength after reclaiming used or stored oil indicates the selective removal of dissolved decay products whereas, the shift under the longer wavelength indicates an increase in content of the dissolved decay products in the oil. Thus it indicates the condition of transformer oil. The complete setup of the procedure discussed above is shown in Fig. 2.

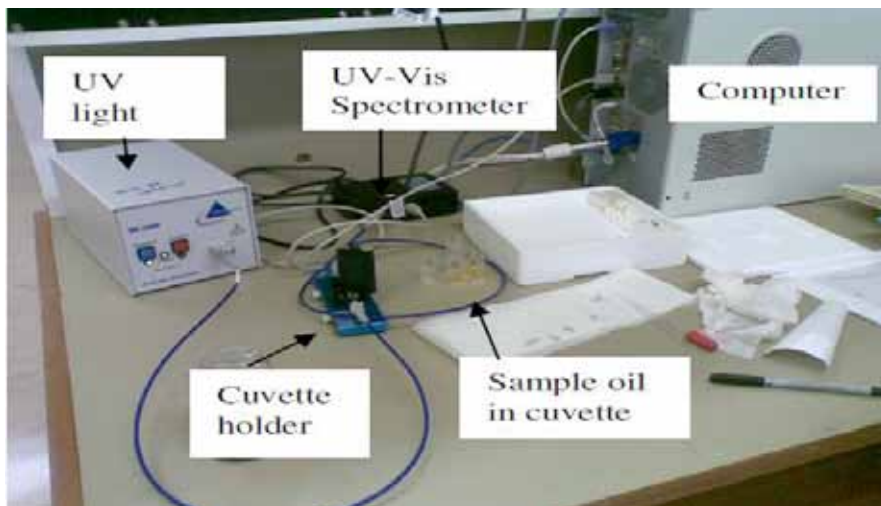


Fig. 2 An assembly of UV/VIS with oil samples and PC interface

The assembly shows the complete setup of UV Spectrophotometer, the function of each equipment is as explained above. The graphs obtained from the UV Spectrophotometer for different oil sample are shown in Fig.3.

Fig. 3(a) shows the UV spectrophotometer plot obtained from the Heptane sample which forms the base line. This is done to fulfil the zero condition of the instrument by adjusting it to read zero absorbance. The value obtained is constant and is equal to -0.082. The wavelength which the instrument is scan is in range of 360-600nm.

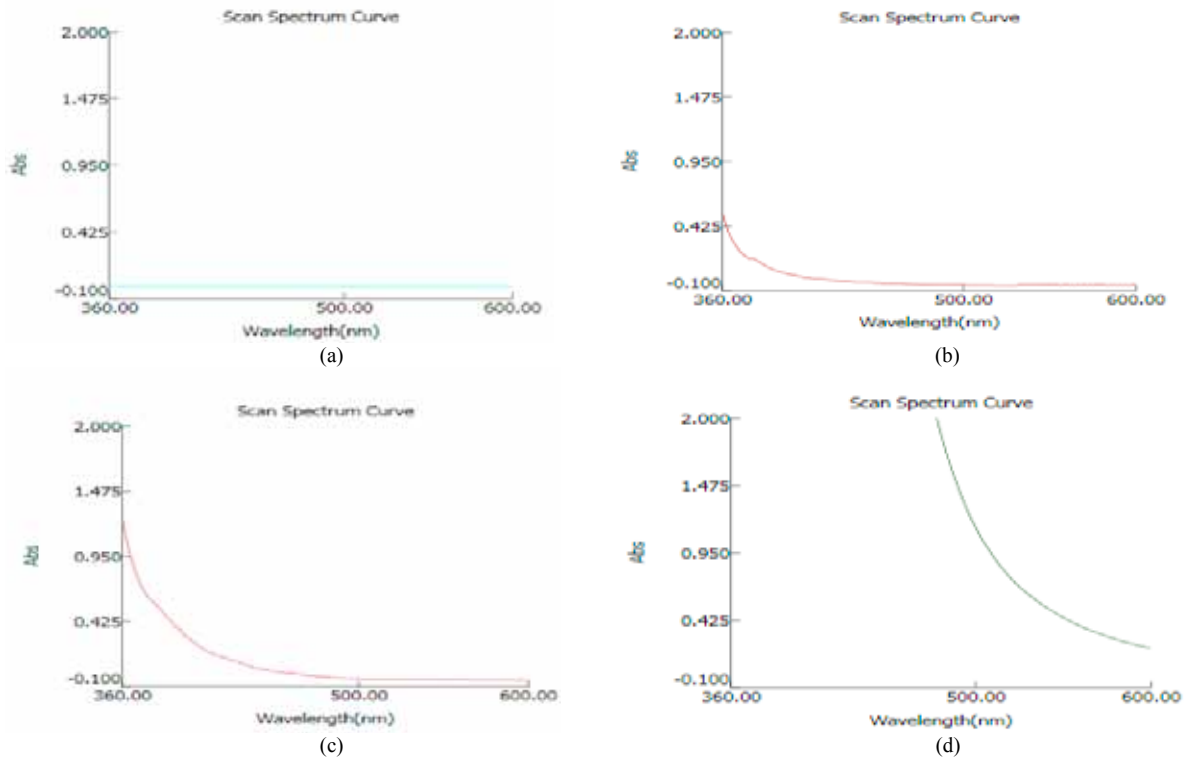


Fig. 3. The graphs obtained from the UV Spectrophotometer for different oil sample are (a) Show the base line (heptane), (b) Fresh transformer oil, (c) Medium age transformer oil, (d) Highly aged transformer oil

Fig. 3(b) shows the UV Spectrophotometer plot obtained for fresh oil sample. For obtaining this graph the heptane-filled cuvette is moved to the reference position as mentioned previously. Now the second glass cuvette is filled with the transformer oil sample and placed into sample holder. Then the UV scan is started to obtain the plot. As it is seen from Fig. 3(b) that there is a shift of the absorbance curve obtained from UV scan. It is seen that absorbance value decreases from wavelength 360-600nm. Such behavior of the change in the shift of the absorbance curve indicates that the oil is fresh and indicates that there is a removal of dissolved decay products.

The UV Spectrophotometer plot obtained for medium aged transformer oil is shown in Fig. 3(c). The initial value of the absorbance has increased compared to the value in 3(b). The behavior of the absorbance versus wavelength is same but there is deviation in the curve, which indicates the presence of the dissolve decay products and impurities in the oil which due to aging of the oil.

The UV Spectrophotometer plot obtained for highly aged transformer oil is shown in Fig. 3(d). Interestingly the value of the absorbance has increased in this case too as compared to Fig. 3(c). The absorbance curve which is obtained from this graph after UV scan indicates that there is increased content of dissolved decay products in transformer oil. An overall observation of all the plots obtained from the UV spectrophotometer shows that the curve shifts from the lower to higher side if there is a presence of impurities in the sample oil. However, such information will be helpful to the persons who are well conversant with technical background.

The efficiency of the method will be high if it is possible to automatically identify the age of the oil. It will be more useful to the technicians if the information about the age of the oil is identified automatically. Hence, the decisive output regarding age of the oil in terms of characteristics like new oil, medium aged oil and highly aged oil is more useful.

For designing an automatic system the parameters obtained from the UV Spectrophotometer scan can be used. A fuzzy logic based method has been proposed in this paper. The age of the oil is classified as new, medium and highly aged oil. If the oil is not in commission or of 1 year age it categorized as new oil. The oil is of medium age if the oil is tested after 6 years. Finally, the oil sample tested after 10 years is named as highly aged and ageing depends on then contamination in the oil not in the basics of years.

#### 4. Fuzzy Logic Based Dissolved Decay Product Estimation

The parameters used as input for the fuzzy logic model of this research will be the UV-Vis spectral response wavelength and its absorption. These two parameters will be used in estimating the decay product availability in the oil. Even though this method by Fuzzy Logic approach is less precise than ASTM D6802-02, their use is closer to human intuition because it is built on rules from human experiences and not based on formula.

With a sufficient amount of data, fuzzy logic can be convenient way to map an input space to an output space. Mapping input to output is the starting point of all fuzzy logic modeling. The graphical presentation of an input-output map for the model that present the decay product based on UV-Vis spectral response absorption and wavelength is shown in Fig. 4 as shown in Figure inserting UV-Vis range absorption and wavelength into the fuzzy logic model, the output from the model is the decay product value.

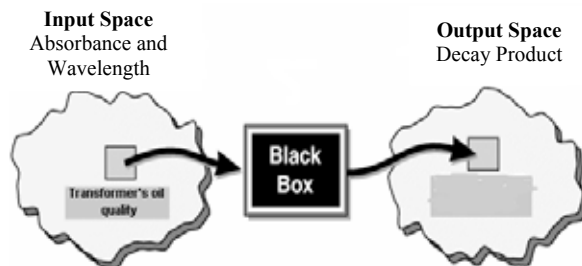


Fig. 4 Input-Output map for decay product estimation

##### 4.1 Fuzzy-Model

Fig. 5 shows the fuzzy model that is summarizing the procedures for the software development of decay content estimation based on Fuzzy Logic approach. The model is built by using the graphical user interface tools provided in MATLAB. This is the design detail procedures of the “Black Box” in Fig. 4. Inputs variable for the model are the values of absorption test wavelength and maximum absorption collected from UV-Vis spectrometry test.

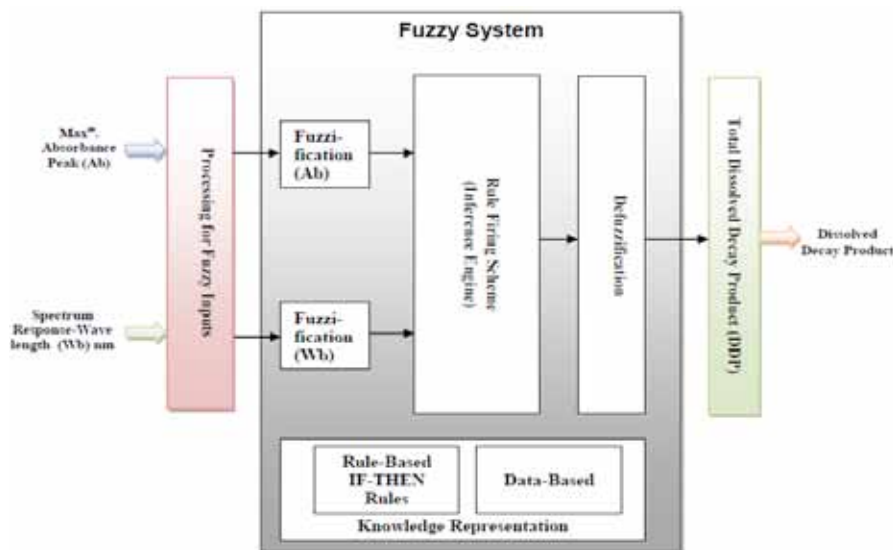


Fig. 5 Fuzzy Inference model for DDP measurement

4.2 Input-Output System Modelling in MATLAB

A Fuzzy Logic simulation model was developed using MATLAB [14]. The simulation model was able to predict the decay product based on the input parameters of UV-Vis spectral response wavelength and absorption value. The corresponding curve for the input variable of wavelength, maximum absorption peak and corresponding 13 sets of fuzzified triangular shaped membership (for simplicity but not necessary, other membership functions i.e. trapezoidal, gaussian, generalized bell can also be used) are depicted in Fig. 6. The simulation model was able to predict the decay products based on the input parameters of UV-Vis spectral response wavelength and absorption maximum peak value.

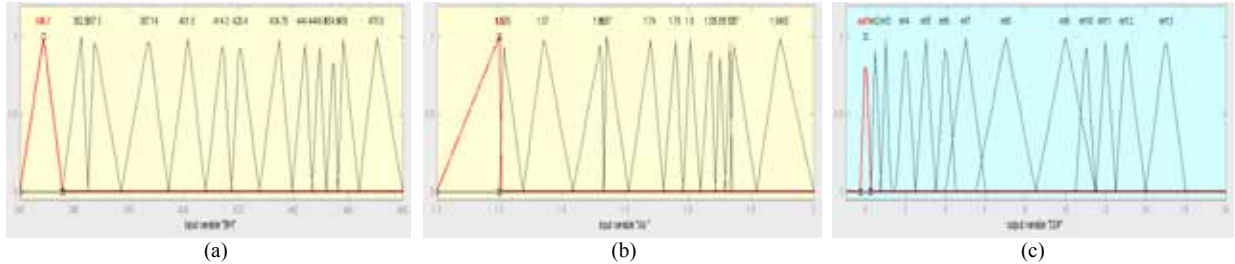


Fig. 6 Triangular combination membership function curves for UV-Vis of (a) absorption bandwidth; (b) for maximum absorption peak and (c) for decay product output

The Fuzzy Logic model is governed by IF-Then rule. As there are 13 sets of membership function available, a total of 13 set of rules were added into the system to allow the system to aggregate across all possible outcomes.

The completed decay estimation model is shown in Fig. 5 the model developed was able to estimate the decay product with more than 99.06% accuracy compare to spectrophotometer result as shown in table no. 1. Variable wavelength and absorption represent the spectral response bandwidth and peak absorbance respectively, as an input data to the fuzzy model and t is the step time for the fuzzy model simulation. Fig.7 (a) illustrates the interface which shows the estimated decay content level based on the input of wavelength and absorption peak to the decay product output is illustrated in a three-dimensional graph shown in Fig.7 (b).

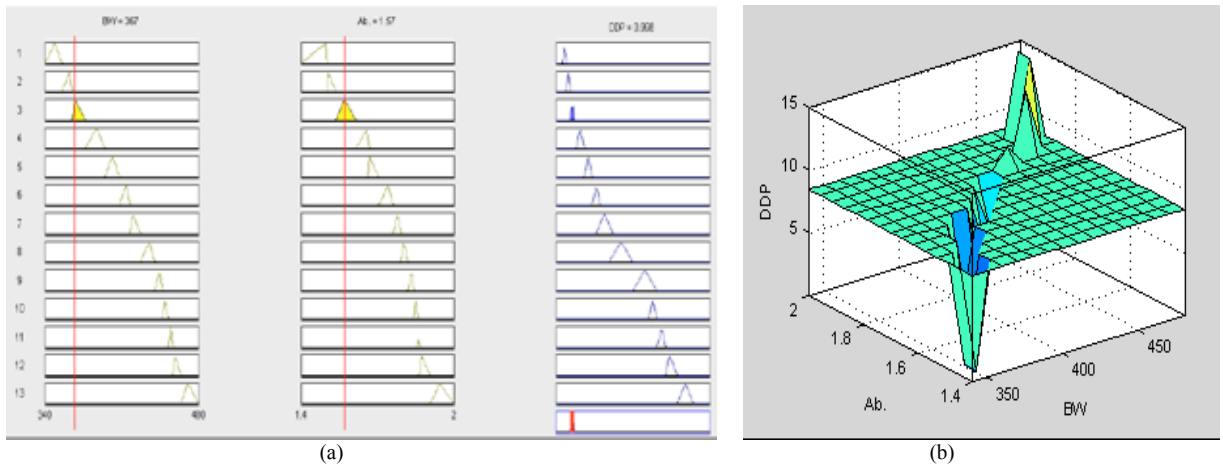


Fig. 7. (a) Decay concentration level estimation display based on the wavelength and absorption peak inputs, (b) Illustrated decay product output representation in a three-dimensional graph

5. Result and Discussion

The simulation model developed was able to estimate decay content with more than 99.06% accuracy compared to the measurement result from ASTM D6802-02 as shown in table no. 1. The maximum range of the output parameter is sufficient to indicate the deterioration of solid insulation inside the transformer. As the decay contents

higher, the possibility of transformer failure is very high. Summary of the percentage of error for the simulation model compared to spectrophotometer measurement result is shown in Table 1.

Table 1 Comparison between simulation and field measurement result

Sample No.	Inputs		Outputs		Percentage of error (%)	Percentage of accuracy (%)
	Spectra response Bandwidth (nm)	Maximum absorption peak (Å)	ASTM D6802-02 Decay product	Simulation model Estimation Decay product		
1	348.76	1.5000	0.0	0.00937	-0.937	99.063
2	362.55	1.5045	0.5	0.498	-0.40	99.502
3	367.32	1.5710	1.0	0.998	-0.20	99.80
4	387.14	1.6625	2.0	2.01	+0.50	99.50
5	401.55	1.6700	3.0	3.0	0	100
6	414.33	1.7410	4.0	3.99	-0.25	99.75
7	420.39	1.7805	5.0	5.0	0	100
8	434.76	1.8030	7.0	7.0	0	100
9	444.44	1.8360	10.0	10.0	0	100
10	449.50	1.8510	11.0	11.0	0	100
11	454.80	1.8670	12.0	12.0	0	100
12	458.07	1.8715	13.0	13.2	+0.53	99.47
13	470.51	1.9465	15.0	15.0	0	100

## 6. Conclusion

In this paper, fuzzy logic method based on UV Spectrophotometer absorbance values is used for automatic health assessment of the transformer oil. Various samples of oil have been taken and the curve is a plot through which the condition of oil is determined. The outputs obtained from the fuzzy logic method are compared with the UV/VIS response. It is found from comparison that all the results obtained from fuzzy logic are same with accuracy of 99.06% as obtained from the UV spectrum. The results obtained are very efficient and fast. Such information is highly needed for a person at the monitoring point.

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